RECENT RESEARCH ON WAYS TO IMPROVE TIRE TRACTION ON

WATER, SLUSH OR ICE

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Langley Station, Hampton, Va.

Presented at the
AIAA Aircraft Design and Technology Meeting

Los Angeles, California
November 15-18, 1965

L-4784

[redacted]

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ABSTRACT

This paper first discusses the three main factors that can cause almost complete loss of tire traction on wet runways: namely, dynamic hydroplaning, viscous hydroplaning, and tire tread rubber reversion. The first two factors have been well defined by previous research but only recently has the latter factor, tire tread rubber reversion, been shown to produce very low friction coefficients. The paper then discusses how pavement surface texture, runway water depth, tire tread design, vertical tire load, and tire inflation pressure interact with these factors. A method for measuring average texture depth of a runway surface is given. This method shows promise as a means of classifying runway surfaces as to their slipperiness when wet. Finally, tests of two promising methods for increasing tire traction on wet runways are described and results discussed: namely, air jets placed in front of tires and pavement grooving.

INTRODUCTION

The extreme loss of tire braking and lateral traction that sometimes occurs to aircraft during landings on wet and flooded runways is of utmost concern to the aircraft community for obvious safety reasons. The term hydroplaning, or aquaplaning, is usually used to describe this drastic traction loss whenever it occurs. Very few statistics are available to indicate the frequency of occurrence of hydroplaning. However, one major U. S. airline estimates that 5 percent of the landings of its fleet each year are made on wet runways. It further estimates that one out of every 500 wet landings encountered hydroplaning in some form with the attendant loss of tire traction contributing to making the aircraft tend to depart from the runway sideways in some cases (crosswind) and to overrun the runway in other cases. Other airlines having similar route structures in this country appear to show similar results. Fortunately, most of the cases cited were not accidents but were incidents where the pilot did not lose complete control of the aircraft, and was able to keep the aircraft within the confines of the runway during landing. It should be noted, however, that the margin between an accident where damage or injuries are suffered and an incident where no aircraft damage or passenger injuries occur, is very small indeed. The possibility of the aircraft losing traction capability as often as once every 500 wet landings indicates the urgent need for developing some method or device, either on the runway or on the aircraft, that will alleviate the drastic traction loss during take-off and landing and thus increase safety of flight.

Since 1960, the landing loads track of the NASA Langley Research Center has been extensively employed in tire hydroplaning research (refs. 1 to 18). This research enabled two different types of loss of traction on wet surfaces to be separated and defined: namely, dynamic and viscous hydroplaning. It was found that for dynamic hydroplaning to occur, the runway must be flooded beyond a critical fluid depth, and the aircraft must be traveling at a speed in excess of a critical ground speed (referred to as the hydroplaning speed, and which is dependent upon the square root of the tire inflation pressure used on the aircraft). It was found, on the other hand, that viscous hydroplaning required: a thin fluid film to be present on the runway; a critical aircraft ground speed (much lower than for the dynamic hydroplaning case which was dependent upon the viscosity of the runway fluid); and a very smooth runway surface. Fortunately, it was found that the texture existing on most runway surfaces is sufficient to break up and dissipate the thin viscous film creating this type of hydroplaning. Viscous hydroplaning thus will be a serious problem only on very smooth runway surfaces.

Studies of aircraft skidding off the runway sideways and overrun accidents and incidents have, however, disclosed a significant number of cases that could not be fully explained by either the dynamic or viscous type of hydroplaning. These studies also disclosed that in most of these nonconforming accidents or incidents, white streaks were usually developed in the tire paths on the wet runway, and that the tires showed evidences of a "reversion" of the tread rubber to an uncured form in the skid patches developed on the tread surface.

In a research program initiated at the track recently, a series of tests was made with the aircraft tire locked to prevent rotation so that the tire was forced to skid along the wet and flooded test runway surfaces at different ground speeds. During these tests, the tires developed tread rubber reversion in the skidding footprint region, and extremely low friction coefficients were measured down to speeds as low as 25 knots.

Thus it will be the purpose of this paper: to illustrate briefly the effects of dynamic and viscous hydroplaning on tire traction performance; to describe the effects of prolonged tire skids and tread rubber reversion on aircraft braking and directional control; to briefly describe several methods to improve aircraft tire traction on wet runway surfaces; and finally to describe a method of measuring the average depth of texture as a means of classifying runway surfaces as to their slipperiness when wet.

SYMBOLS

F_z	vertical load, lb
p	inflation pressure, lb/in.^{2}
V_P	dynamic hydroplaning speed, knots
μ	instantaneous tire-ground friction coefficient
μ_{av}	average friction coefficient between slip ratios of 0.10 and 0.50
μ_{eff}	effective friction coefficient (average μ developed by aircraft as modified by pilot braking or anti-skid system)
μ_{max}	maximum friction coefficient
μ_r	rolling resistance coefficient
μ_{skid}	skidding friction coefficient (friction coefficient at slip ratio of 1)
μ_{static}	maximum friction coefficient obtained at extremely low ground speeds (0.008 to 1.7 knots)

TIRE BRAKING TRACTION ON DRY RUNWAYS

This section on braking traction of tires on dry surfaces is given to provide background information and also to serve as a basis of comparison for the traction results obtained on wet surfaces to follow.

Slip Ratio Effects

When rolling tires are forced by braking action to slow rotation from a free-roll condition to a locked or full-skid condition, the friction coefficient developed between tire and ground varies with slip ratio in the manner shown schematically in figure 1. With no braking (slip ratio zero) the lower limit of friction coefficient, μ_r is determined by the resistance of the rolling tire, wheel bearings, and unloaded brake. Under normal tire operating conditions, μ_r usually falls within the range 0.02 - 0.05 friction coefficient. As braking torque is applied to the wheel, the friction coefficient rises until it reaches a maximum value at μ_{max}. It should be mentioned that up to this point practically no sliding or slipping occurs between the tire footprint and ground. The apparent slip shown up to the region of μ_{max} in figure 1 is due to the torsional elasticity of the tire. After μ_{max} is attained, unless the brake torque is rapidly decreased, the tire quickly locks up at a friction coefficient, μ_{skid}, usually considerably lower than μ_{max} as indicated in figure 1 and as is shown by data in figure 2. The locked wheel skid is a highly undesirable condition for the tire at high speeds on dry runways. Shown in figure 3 is a tire which blew out after sliding only 60 feet at 100 knots ground speed on a dry concrete runway under a vertical load of 10,000 pounds. Calculations show that up to the point that the tire blew out, the contact patch of the tire, which was approximately 40 square inches in area, was absorbing 460 horsepower. No wonder that one inch of tread rubber and carcass cord was melted and eroded away in less than 0.36 second, the duration of the locked wheel skid in this case. To avoid such an occurrence is, of course, a primary reason for installing anti-skid braking systems on aircraft. The optimum anti-skid system would be one that would ride the peak of the μ-slip-ratio curve in figure 1, and thus produce maximum braking and avoid excessive tread wear. Actually this is very difficult to achieve in practice and the average friction coefficient, μ_{av}, developed between slip ratios of .10 and .50 is probably more representative of what efficient anti-skid systems actually achieve.

Inflation Pressure and Vertical Load Effects

Data given in reference 19 indicate that the maximum tire-ground friction coefficient obtained at very low ground speeds (hereafter called μ_{static}) tends to decrease with increasing tire-ground bearing pressure on a dry runway. The data shown in figure 4 illustrate this trend. The tire inflation pressure represents a reasonable approximation of the average bearing pressure developed between tire and ground although tire carcass stiffness and tread effects introduce some small differences. These data taken from reference 19 were obtained at extremely low ground speeds ranging from 10 inches per minute (0.008 knots) to 1.7 knots. These data, representing many airplane tire sizes, also show that μ_{static} may be approximately predicted for the range shown by the empirical equation:

$$\mu_{static} = 0.93 - .0011\ p \tag{1}$$

The effect of vertical load changes on friction coefficients on dry surfaces is practically nil (since the tire acts as an elastic body over practical tire load ranges.) There is, however, a rise in tire inflation pressure due to the internal volume of the tire diminishing as the tire deflects under increasing vertical load, but this effect is rather small under rolling conditions during landing. For example, the pressure rise due to loading a tire from zero to rated deflection (rated load) is approximately 2 to 3 percent of the initial inflation pressure. As can be seen from figure 4, this pressure change will not modify the friction coefficient to any great extent.

Speed and Pavement Surface Texture Effects

The effects of pavement surface texture and speed on dry runway braking effectiveness are shown by figure 5. The data shown indicate that pavement surface texture or material has relatively little effect, while increasing ground speed tends to decrease the braking effectiveness somewhat. It is believed that the decreasing trend of μ_{av} with speed is primarily due to inertia effects acting on the deflecting tire as it rolls through the ground contact zone. These inertia effects tend to reduce the tire-ground contact area as speed increases and thus create a higher bearing pressure and hence from figure 4 a lower friction coefficient. Tire tread temperature and other as yet unknown effects may also contribute to this decrease. It should be mentioned that very smooth surfaces tend to give somewhat lower dry friction values than the values obtained for the textured surfaces shown in figure 5. Also shown in figure 5, by the horizontal dashed lines, are the predicted values of μ_{static} obtained from equation (1). It can be seen that these calculated values predict reasonably well the experimental μ_{av} values obtained at low ground speed.

Figure 5 also presents rolling resistance values (μ_r) obtained from reference 17. These data indicate that the aircraft tire free rolling resistance, in contrast to μ_{av}, tends to increase with increasing ground speed.

Summary Remarks on Tire Braking Performance on Dry Runways

The braking performance of aircraft tires on dry runways may be summarized as follows:

1. Maximum braking is achieved over a slip ratio range from about 0.1 to 0.3. Operation at lesser slip ratios reduces the braking action but has the advantage of having all the stopping energy being absorbed by the brake and hence very little tire tread wear develops. Operation at greater slip ratios than 0.1 to 0.3 also results in reduced braking action, but increases tire tread wear since the energy absorbed in stopping is now divided between the brake and the partially skidding tire. Operation at a full skid condition

or slip-ratio 1 results in no energy being absorbed by the brake, reduced braking action, and intolerable tire tread wear.

2. Next to slip ratio, the tire inflation pressure has the largest effect on braking friction coefficient with increasing pressure tending to decrease the maximum attainable values. For example, doubling the tire pressure from 100 to 200 pounds per square inch results in μ_{static} decreasing from about 0.82 to 0.71. Increasing ground speed also tends to reduce the dry braking effectiveness. For example, increasing speed from 30 knots to 100 knots (figure 5) results in μ_{av} dropping from 0.77 to 0.68, a 13 percent reduction. Elevating the temperature of the tread rubber also has a pronounced effect on reducing braking effectiveness (see fig. 2), but the fall-off in braking friction with rubber temperature is not known for tires operating under full scale conditions.

3. Pavement surface texture and tire tread design apparently have little effect on dry runway braking effectiveness for all conditions of load and pressure. Some available data, however, show a reduction in braking effectiveness on very smooth dry runway surfaces.

TIRE BRAKING TRACTION ON WET OR FLOODED RUNWAYS

This section of the paper is concerned with describing the three main factors which, acting separately or in combination, can degrade tire braking traction to extremely low values on wet surfaces. These factors are dynamic hydroplaning, viscous hydroplaning, and tire tread rubber reversion.

Dynamic and Viscous Hydroplaning Effects

Considerable research has been carried out on both dynamic and viscous hydroplaning in recent years. (See refs. 1 to 18.) Essentially, hydroplaning may be defined as the condition under which the tire footprint is actually lifted off the runway surface by the action of fluid pressure and then rides on a fluid film of some finite thickness. Since fluids cannot develop shear forces of appreciable magnitude, tire traction under this condition must drop to negligible values. Water pressures developed on the surface of the tire footprint and on the ground surface beneath the footprint have been measured during a recent investigation at the landing loads track (ref. 16). This research showed that it was possible for this water pressure buildup under the tire footprint to originate from either fluid density or fluid viscosity, depending upon conditions; hence the need to classify hydroplaning into two types.

Both hydroplaning types are illustrated in the following figures (figs. 6 to 8). Also shown are the effects of vertical load, inflation pressure, fluid depth, and pavement texture on hydroplaning. It should be mentioned that the data shown in these figures were obtained during a recent investigation at the landing loads track where five pavement surfaces were placed in line. The test tire was braked in succession from a free roll to a locked wheel, and then allowed to return to the free roll condition on each of these surfaces as the test carriage proceeded down the track. The first test surface encountered was a smooth, steel-troweled, concrete surface having an average texture depth of 0.04 mm as determined by a method to be described later. The next surface was a more textured float-finish concrete having an average texture depth of 0.19 mm. The next two test surfaces were asphalt, the first of these using a small aggregate to produce an average texture depth of 0.34 mm. The second asphalt surface was classified as large aggregate (stone size did not exceed 1/2-inch in dimension) and had an average texture depth of 0.56 mm.

The fifth and final surface was smooth wet ice. To obtain this surface, a 200-foot length of the track was refrigerated and water placed on this surface frozen. At the time of testing, the ice surface was lightly sprayed with water to produce a water film on the ice surface.

Damp runways.- A series of smooth-tread braking tests was made on the five test surfaces just described under the following condition of wetness. All test surfaces except ice were flooded with water to a depth of 0.1 to 0.2 inch. The water was then allowed to stand until the surfaces were thoroughly saturated. Just before the test runs were made, the standing water was removed from each of the test surfaces by means of stiff bristle type brooms. This action left each of the test surfaces without any standing water, but damp to the touch and discolored in appearance (from dry condition). Each test run was made immediately upon reaching this wetness condition. The damp surface condition was selected to minimize dynamic fluid pressure buildup. Any traction loss suffered by the test tires under this damp condition would therefore be primarily due to viscous type hydroplaning. The results from this study are shown in figure 6.

Also shown in figure 6 is the dry traction curve (from fig. 5) obtained for the same load and inflation pressure conditions. These data indicate that the water film present on the damp smooth concrete surface was sufficient to produce viscous hydroplaning, down to very low ground speeds. It can be seen that the values obtained on damp smooth concrete are essentially as low as those obtained on wet ice! The effect of pavement texture in reducing viscous hydroplaning effects is strikingly illustrated by noting the decrease in traction loss encountered by the textured pavement surfaces under damp conditions in figure 6.

Flooded runways.- The effect of flooding the test surfaces on smooth tire braking effectiveness is noted and compared with damp surface data in figure 7. This figure shows only the results obtained on the smooth concrete and large aggregate asphalt test surfaces. The data obtained for the other test surfaces were omitted for clarity, but showed similar trends according to the degree of texture of the test surface. In this instance (fig. 7), the test runways were flooded to a depth of 0.1 to 0.2 inch and the test runs were performed immediately upon reaching this depth. It can be seen that for the large aggregate asphalt surface, this flooding resulted in a large increase in traction loss over the damp results at the higher ground speeds, and a total traction loss at about 106 knots, the predicted hydroplaning speed from dynamic hydroplaning theory (ref. 12). The double cross-hatched area in this figure indicates the loss attributed to dynamic hydroplaning for the asphalt surface. Turning to the smooth concrete results, it can be seen that flooding this surface resulted in increasing the friction coefficients slightly over the damp values. This increase is attributed to the larger fluid drag created by the tire displacing water from the tire path at speed under the greater water depth condition. Obviously, the smooth tread tire must be already in a hydroplaning state on the damp smooth concrete surface, and further increasing the water depth has little effect.

Vertical load and tire inflation pressure effects.- Reference 16 states that viscous hydroplaning is not greatly affected by changes in tire vertical load and inflation pressure. This conclusion is amply borne out by the data shown in figure 8 for the flooded smooth concrete surface.

It has already been concluded from the previous discussion on figure 7, that the drastic traction loss with speed on this surface was due to viscous hydroplaning regardless of water depth. The data in figure 8 indicate that approximately doubling the vertical load (from 12,000 pounds to 22,000 pounds) and tire inflation pressure (from 140 pounds per square inch to 290 pounds per square inch) affected μ_{av} only slightly for this surface.

Dynamic hydroplaning, as further stated in reference 16, was insensitive to vertical load changes but was greatly affected by the tire inflation pressure. This conclusion is also verified by the data of figure 8 obtained on the textured pavements. It can be seen that the data for $p = 140$ pounds per square inch tend toward minimal values at its critical dynamic hydroplaning speed value of 106 knots while the data for $p = 290$ pounds per square inch tend toward its minimal value of 153 knots. It should also be noted that while raising inflation pressure increases the wet traction at high speeds, the traction at low speeds is reduced. This effect results from the fact that μ_{static} (fig. 4) decreases as inflation pressure increases. If one seeks to increase tire traction at high speeds on flooded runways by raising the tire inflation pressure, one must also accept reduced traction values at lower speeds on flooded runways, as well as reduced traction values at all speeds on dry runways.

Pavement surface texture and grooving effects.- The data shown in figures 6 through 8 have demonstrated the importance of providing an adequate texture to pavement surfaces so as to minimize traction losses from viscous hydroplaning. It is also believed (see ref. 16) that the more open-textured type pavement surfaces also help to alleviate traction losses from dynamic hydroplaning by providing more escape paths for the water trapped between the tire footprint and ground. Pavement grooving provides similar dynamic fluid pressure alleviation as shown in figure 9, adapted from reference 20. Some viscous fluid pressure alleviation should also be provided by the sharp edges of the grooves when contacting the tire tread surface. The data shown in figure 9 indicate that the 3/8-inch by 3/8-inch on 2-inch centers transverse grooves investigated, more than doubled the water depth required for dynamic hydroplaning to take place. The frequency of hydroplaning occurring on such a grooved surface is probably very low due to the extremely high rainfall rates required to deposit and maintain a water depth of over 0.4 inches on the runway surface.

<u>Measurement of pavement texture depth</u>.- As can be inferred from the discussions thus far, pavement slipperiness is related directly to the pavement surface texture and its ability or inability to alleviate dynamic and viscous fluid pressure buildup. It thus follows that pavement slipperiness can be possibly correlated with some characteristic of the physical make up of the texture such as asperity size, shape, number per square inch and so on. Research along these lines, for example, is being conducted by Moore (Cornell Aeronautical Laboratory), Kummer and Meyer (Pennsylvania State University), and Sugg (British Ministry of Aviation).

Joyner of the Langley Research Center (ref. 18) has developed a simple grease technique to determine the average texture depth of a pavement surface for use as a characteristic. His method is simply to spread a known quantity of grease on the pavement surface with a rubber squeegee. The object is to carefully cover the complete surface with the squeegee until the grease runs out. The average texture depth for the surface is then the quotient of the grease volume used divided by the surface area covered. An illustration of this grease measurement procedure is given in figure 10. The correlation of average texture depth with braking traction for the test runway surfaces at the track is given in figure 11. It is interesting to note in this figure, that increasing the surface texture increases braking traction up to what appears to be a critical texture depth. Further increase in texture depth beyond this point increases traction only slightly. Photographs of the surfaces are shown in figure 12.

It is important that more correlations of braking traction with average texture depth on actual operational pavement surfaces be undertaken to more clearly define this point. It is also important to use this technique or similar techniques, to survey the runways in operation today in order to define a standard runway surface texture or texture depth. When this is done, then it will be possible to quickly determine when a pavement surface needs to be repaired or replaced due to its poor braking traction qualities when wet or flooded.

Tire tread design effects on flooded runways.- Braking performance of smooth tread aircraft tires on most wet or flooded runway surfaces is greatly improved by cutting or molding a series of circumferential grooves into the tire tread. It has been found that the resulting wet traction improvement over smooth tread tire performance is due to two effects. First, the low pressure channels formed in the tire footprint by the tread grooves and runway surface tremendously facilitate water drainage from the footprint area even under deeply flooded runway conditions. This effect disappears, however, as the critical dynamic hydroplaning speed is neared or exceeded as shown in figure 13. As a result of the better drainage, traction performance of the grooved tire is greatly improved over the smooth tire at sub-hydroplaning speeds. It is important, however, to note in figure 13 how rapidly this benefit is lost as the tire tread wears, or as the groove depth decreases.

The second effect to be discussed is the ability of the sharp edges or corners of the tread grooves to penetrate and displace the viscous fluid film separating the tire from the pavement. Adhesion between tire and ground is thus regained along the line of pavement contact of the groove edges, which increases traction of grooved tires over smooth tread tires on the smoother wet pavements. Automobile tire manufacturers have found that the addition of closely spaced sipes or small knife cuts in the rib areas of circumferentially grooved tires increases traction on wet smooth surfaces to a much greater extent than grooving alone provides. Up to this time this feature has not been provided in high performance aircraft tires due to tread chunking or tread retention problems. With the rapid advances that have been made in the last few years in rubber compounding which have improved tread cutting and retention characteristics greatly, the siping of aircraft tires should be reexamined.

Tire tread design effects on wet runways.- Grooving tire treads shows to even greater advantage when runways are just wet and puddled (water depth less than tread groove depth) than when the runway is deeply flooded. In this case, water drainage in the tread grooves does not become choked until speeds in excess of the hydroplaning speed are attained as shown in figure 14. Again, this benefit decreases as tread wear increases, or as groove depth decreases.

Tire tread design effects on ice-covered runways.- For a number of years, tire manufacturers have been requested to provide aircraft operators with "ice-grip" tires. These special tires have thousands of chopped up pieces of small diameter wires molded into the tire tread that become exposed as the tread surface wears. It is widely believed that this feature increases the grip of the tire on icy pavements. At the request of the Air Force, three "ice-grip" tires having different wire content were tested on the ice-covered runway of the track this past summer, and the results obtained are shown in figure 15. It can be seen that the ice-grip feature does not provide a radical improvement in traction on the ice surface over that obtained with a smooth tread tire without the wire. It is not known at this time whether this improvement resulted from the ice-grip feature or from the three-grooves or the ice-grip tire tread design. It should be noted that the four tires tested were constructed using the same mold and rubber compounds, and only the wire content and groove design varied between the tires. Since the traction values obtained by the "ice-grip" tires do not exceed greatly the free rolling resistance of the tire on dry pavements (fig. 5), it is concluded, the ice-grip feature has little effect on tire traction for the wet ice conditions investigated.

Fluid viscosity and slush effects.- It was demonstrated in reference 16 that increasing fluid viscosity increased the fluid pressures developed between tire and ground. This results in viscous hydroplaning occurring at lower ground speed as the fluid viscosity is increased, or a greater traction loss at the same speed when two fluids of differing viscosity are compared. This result is illustrated by figure 16. It can be seen that traction loss at low speeds (where dynamic effects are unimportant) is much greater on the more viscous slush than on the water-covered runway. These tests were conducted on a moderately textured concrete runway. It is believed, but not substantiated, that these losses could be decreased by increasing the texture of the surface.

Tread Reversion Effects

Examples of skidding accidents.- A recent survey of conditions that prevailed during landing accidents on wet runways uncovered a very interesting correlation. In numerous documented cases on wet runways involving aircraft departure off the side of the runway or in an overrun (both types of accidents indicate drastic loss of tire traction), the runway surface was found to have developed white streaks in the tire paths, and the aircraft tires showed evidences of prolonged locked wheel skids with indications of rubber reverting to an uncured form evident in the skid patches of the tires. Examples of the two types of accident are shown in figures 17 and 18. In figure 18, an overrun case, it will be noted that the white streaks persisted down to the point that the aircraft stopped.

In contrast, on dry runways, if the wheels lock at speed, black streaks from molten rubber eroding from the tire are immediately deposited in the tire paths. While friction decreases under this condition, still at least 1/3 of the maximum dry friction coefficient is available for stopping the aircraft, as shown in figure 2. It thus appears that some mechanism other than viscous or dynamic hydroplaning must be at work to prevent the skidding tire on wet textured pavements from contacting the pavement and developing traction, especially at the very low ground speeds indicated.

<u>Examples of reverted rubber in skidding footprints</u>.- The reverted rubber tread condition was pointed out as early as 1943 by Hardman and Gough in an unpublished memorandum of the Dunlop Rubber LTD., England. In this case, the reverted rubber developed during locked wheel skids on wet grass (see fig. 19). Hardman and Gough stated that, "Examination of the tread blisters revealed that the deterioration was of a fine porosity in a thin layer parallel to and just below (about .02 inch) the original tread surface. This porosity resembled overheating of the rubber due to local attainment of temperatures around 200° C (392° F). The tread surface itself was, however, unaltered and showed the

original surface cracks and fine abrasion marks. This film which was about .01 inches thick showed no trace at all of any effects of high temperature. This surface film was, however, torn away in places having a "scabby" appearance (as shown in fig. 19). The porosity extends under all adhering pieces of surface film and is quite tacky when the latter is torn off." Hardman and Gough further stated that puffs of steam or white smoke were visible at points along the whole length of the "slide" (about 200 or 300 yards) after touchdown.

Further examples of tread reversion are shown in figures 17, 18, 20, 21, and 22. These examples show the tacky porous reverted rubber mentioned by Hardman and Gough but do not show the undamaged surface layer they mentioned. It perhaps was destroyed during the low speed ranges of the skids. Since the examples cited cover such a large range of aircraft types, it is suspected that most aircraft can suffer or experience this phenomenon during prolonged wheel skids on wet or flooded runways.

Duplication of reverted rubber condition during track tests.- A series of tests was made at the track during this past summer with tire locked to prevent rotation on dry, wet, and flooded runways at speeds ranging from about 25 to 100 knots. A typical footprint of a smooth tread tire after a 467-foot skid at 78 knots ground speed on a flooded runway is shown in figure 23. In this particular test, the tire was allowed to skid first along 62 feet of a dry smooth concrete runway to produce molten or reverted rubber in the tread; the rest of the skid took place on the runway flooded to a depth of 0.1 to 0.2 inch. Other tests were made where the skid was initiated on either damp or flooded smooth concrete, and also for an alternately wet and puddled runway condition. Under all conditions of test, if reverted rubber developed in the footprint, the traction values fell to very low values in comparison to those obtained with the tire under normal rubber conditions in the tread (see figs. 24, 25, and 26). As shown in figure 27, the reverted rubber condition tends to make all runway surfaces smooth acting. Pavement surface texture which, as discussed earlier, has such a large effect on traction losses from dynamic and viscous hydroplaning (normal rubber curves), has but little effect for the reverted rubber case for the texture depth range shown.

Formation of reverted rubber in the skidding footprint.- Data at the present time are so limited regarding the formation of reverted rubber in the skidding footprint on wet runways that to discuss it at all may border on speculation. However, some facts are known about the process. Reverted rubber can be obtained readily on dry runways just by skidding the tire a short distance. Perhaps the process is initiated at touchdown on wet runways while the wheels are stopped, depending upon certain as yet unknown pavement texture, wetness, and ground speed conditions.

Generation of steam in the skidding tire footprint, first mentioned by Obertop (ref. 21), offers an explanation for the reverted rubber and the reduced traction that may be developed by tires at very low speeds on textured and untextured surfaces. It may be noted that the steam pressure in the footprint, if developed, must closely equal the tire-ground bearing pressure at all speeds. Moreover, if steam is formed, then it must be super-heated steam, and for aircraft tire inflation pressure ranges, this temperature is sufficiently high to melt the rubber tread surface. Thus, once the reverted condition starts, it is possible to have a steam pump established in the footprint, that keeps reverted rubber forming to effect an efficient seal, which permits high steam pressures to persist right down to a stop on the runway. The steam pressure tends to lift the tire away from the pavement surface and thus reduce traction on wet surfaces in a manner similar to the fluid pressure buildup from viscous and dynamic hydroplaning effects. Steam theory also helps explain the white streaks developed in the tire paths of aircraft during skidding accidents on wet runways. In effect, these paths are being cleared of dirt and other contaminants by high pressure super-heated steam.

With reference to the question of temperature buildup in the footprint, a few preliminary tests were made. In reference 16, a locked automobile tire was allowed to skid up to 257 feet on a smooth runway surface covered with water to a depth of 0.04 inch. A thermocouple embedded in a hole in the tread surface measured the tread temperature close to the tread surface in the footprint. Under these test conditions, insignificantly low tread surface temperature rises occurred over ground speeds ranging from 3 to 63 knots when the automobile tire was inflated to pressures ranging from 16 to 40 pounds per square inch. This result indicated steam was not formed during the automobile tire prolonged skid. On the other hand, a 32 × 8.8 aircraft tire was similarly equipped with thermocouples (see fig. 28) at the track. The peak temperatures experienced by this aircraft tire at the end of approximately 65-foot long skids at 77 knots ground speed on a damp smooth concrete surface, similar in smoothness to the one used for the automobile tire tests, are shown in figure 29. It can be seen from this figure that the peak temperature decreases as the tire inflation pressure decreases which perhaps explains the lower automobile tread temperature. Apparently, temperature buildup on the tread surface of a skidding tire on wet surfaces is related to the unit pressure the tire is developing in the skid patch on the pavement. Further, it will be noticed in figure 29 that tread surface temperatures are higher near the center of the footprint. Another interesting result obtained from this study is shown in figure 30. It can be seen that the temperature of the tread surface rises quickly on the smooth damp concrete surface then falls abruptly when a more textured surface is encountered.

Thus these initial results indicate that reverted rubber may form and possibly provide better sealing around the periphery of the footprint (see fig. 23) than normal rubber, thus allowing a very thin film of water to be trapped in the footprint, heated up, and to possibly change state into steam as predicted by Obertop (ref. 21). This discussion is based on very limited data and it may have to be modified when results of more complete studies of this phenomenon are available.

Multiple reverted rubber skid patches.- The surmise of the previous section, that the reverted rubber may be initiated during the touchdown skid, does not explain numerous cases where multiple reverted rubber skid patches develop around the tire circumference such as shown in figure 21. For these cases, it is believed that intermittent wheel lockups from braking, either pilot or anti-skid actuated, causes the multiple patches. This explanation is borne out by the film sequences shown in reference 22 of the action of an anti-skid equipped bogie landing gear of a supersonic bomber during wet landings. These sequences show wheel lockups for as long as 21 seconds, and successive wheel lockups before the wheels have regained free roll rotational velocity. Thus, the anti-skid system appears to permit the tires to operate (for this low tire-ground friction coefficient regime) on the back side of μ-slip-ratio curve of figure 1.

Summary Remarks on Tire Braking Traction on Fluid-Covered Runways

The preceding sections of the paper have attempted to show that viscous hydroplaning, dynamic hydroplaning, and tire tread reversion all can, depending upon conditions, create total loss of tire traction on fluid-covered pavements. Fortunately, the critical conditions required of the tire, pavement, or aircraft for each of these phenomena to achieve total traction loss are different. This makes possible certain avenues of approach to combat and alleviate each hydroplaning type. For example, the critical parameter for viscous hydroplaning is pavement surface texture. If an adequate texture is provided on the runway surface, then, viscous losses are greatly alleviated over all operating speed, inflation pressure, and tire tread condition ranges.

On the other hand, the critical requirement for dynamic hydroplaning to occur is fluid depth on the pavement. Removing the fluid from the tire paths, by air jets or otherwise, eliminates dynamic hydroplaning as a problem. This is what tire tread designs can do satisfactorily up to a certain ground speed dependent upon inflation pressure and fluid depth conditions. Once this critical ground speed is exceeded, then total traction loss occurs until either the speed or the fluid depth is reduced below critical values.

Finally, let us discuss the tread reversion case which develops during a prolonged wheel skid. It is potentially the gravest problem because the minimum requirement for it to occur, as far as the condition of pavement is concerned, appears to be only that it be smooth and damp (which can happen practically every time it rains). The prevention of tread reversion can be stated simply but may be difficult to achieve in practice; it is, prevent the wheel lockup, or keep the wheel turning under all braked and unbraked conditions on the runway.

The alleviation of traction losses on wet runways not only by viscous and dynamic hydroplaning but also by tire tread reversion has been the subject of recent and continuing research at the landing loads track. Some of the more promising means that have been studied are discussed in the following section of the paper.

SOME PROMISING MEANS OF IMPROVING TIRE TRACTION ON WET SURFACES

Pavement Surface Texture

The paramount importance of pavement surface texture in alleviating viscous traction losses has been discussed at length in this paper. Until recently, the texture condition of the surface of an average runway has not been defined, except loosely in terms of word adjectives. One really did not know whether or not a particular surface had an adequate texture when wet. It is now felt that the fundamentals of traction losses on wet runways are well enough understood so that a standard or reference runway surface can be defined.

It is important, for this purpose, to be able to describe quantitatively the relative slipperiness of pavements in terms of some easily measured pavement surface parameters such as the average texture depth described earlier in the paper. In addition, the work of Moore (Cornell Aeronautical Laboratory), Kummer and Meyer (Pennsylvania State University), Sugg (British Ministry of Aviation) and others has pointed in this direction. It is suggested that these techniques be carefully studied and the most promising one selected for use in a survey of a statistical sample of operational runway surfaces in use today. In this survey, the frictional qualities of the surfaces when wet must also be determined. The most direct but also most expensive way to establish the correlation between wet braking friction and pavement texture would be to conduct braking tests using full-scale aircraft. It is felt that the use of instrumented ground-based vehicles should not be ruled out for this purpose. As a contribution to the development of the use of ground-based vehicles for measuring aircraft-to-runway traction, the following discussion is offered.

Previous friction correlations taken with ground-based vehicles have not accounted for the usually widely different tire inflation pressures that exist between aircraft and ground vehicles. As can be seen from figure 4, inflation pressure has a pronounced effect on the magnitude of μ_{static}, which is representative of the ultimate traction any runway surface can develop (see also fig. 5). For example, a ground-based vehicle using tires inflated to 25 pounds per square inch should develop a μ_{static} value of 0.9 (from fig. 4), whereas a fighter type aircraft tire with an inflation pressure of 300 pounds per square inch should develop a μ_{static} value of only 0.6. It is believed that this inflation pressure effect is chiefly responsible for the difference existing between various aircraft and ground-based vehicle traction measurements. A possible means of taking the inflation pressure effect into account would be to normalize and to divide the friction coefficients obtained during aircraft or ground vehicle tests by the appropriate μ_{static} value for the tire inflation pressure used. Thus any of the ratios $\frac{\mu_{max}\ (wet)}{\mu_{static}}$, $\frac{\mu_{av}\ (wet)}{\mu_{static}}$, or $\frac{\mu_{skid}\ (wet)}{\mu_{static}}$ (if obtained at low speeds) could be used to denote the relative slipperiness of a pavement, with a ratio 1 indicating a surface having no wet traction losses. This process should make ground vehicle measurements correspond more closely to aircraft traction measurements.

Moreover, because of the large but varying effects of tire tread design on braking traction on wet surfaces, the vehicle test tires should have smooth treads for the purpose of pavement slipperiness measurements. Further, the tests should be conducted on a wet but not flooded runway surface to minimize dynamic pressure effects on the measurements. The test speed should be fairly low, say the order of 30 miles per hour, again to minimize dynamic pressure effects on the measurements. Such a test speed would permit a traverse to be made of a 10,000-foot runway in about four minutes, certainly a not unreasonable shutdown time for an operational runway. Finally, the method should compare the values of the particular ratio selected, say $\frac{\mu_{max}}{\mu_{static}}$, with measured values of the pavement texture characteristic selected, say average texture depth (from Joyner). In this way, the results of the survey could be expressed in terms of a slipperiness number where 1.0 represents the ideal texture range (no losses). The survey would establish a range of texture depths giving satisfactory operation and also indicate the range of texture depths associated with unsatisfactory operation.

Research should be continued on pavement surface textures until it is possible to define the optimum texture range required for both satisfactory wet runway traction performance and tire tread life. The photograph of figure 31 demonstrates a significant point. It can be seen that for the accident involved, the tire paths of the aircraft left white streaks on the runway in the picture foreground. At the point where a definite change in surface texture occurred on the runway, black streaks developed in the paths. From this, it appears that some surface textures can remove the dangerous reverted rubber from the tire and normal braking characteristics are regained. Research in this area should be emphasized.

Use of Air Jets to Improve Tire Traction on Wet Runways

Air jet research to improve tire traction was first performed at the Langley Research Center in 1958; the results of this initial work, performed on a small wheel and belt arrangement, are reported in reference 23. Air jet research at Langley was resumed at the landing loads track during the summer of 1964, and some of the results obtained during this investigation are described.

Figure 32 shows a view of the test fixture and air jets used in the current test program. The test tire was a regular 6.50 - 13 automobile tire inflated to a pressure of 27 pounds per square inch. Both a smooth-tread and a 4-groove ribbed-tread tire were tested. Essentially, the air jet arrangement, as shown, was a tandem-nozzle arrangement with the trailing nozzle located about 7-1/2 inches behind the front nozzle and about 10 inches in front of the tire. The tire in this figure is resting on a glass plate which was located flush with the concrete surface in the test runway. From beneath this glass plate, pictures of the tire footprint were taken as the tire traveled across the plate. The water over the glass plate was colored with a green sea-marker dye to give better picture contrast. These pictures showed the very beneficial effect which can be obtained by completely clearing water from the footprint at speeds well above the hydroplaning speed. (For example, see figure 33.) The left portion of figure 33 shows the tire in a completely hydroplaning condition when traveling at a speed of 54 knots. The right portion of figure 33 shows the good contact of the tire with the runway when the tire is traveling at a speed of 87 knots; this beneficial effect was obtained with the use of air jets. In this case, hydroplaning has been alleviated. In addition, quantitative measurements were made of friction coefficient and hydrodynamic pressure developed between the tire and test runway surfaces.

The surface of the test runway shown schematically in figure 34 was very smooth, except for a 52-foot section in the middle which was sandblasted in order to have a surface texture somewhat more representative of highways and runways in use today. For example, the beginning of the sandblasted concrete surface had an average texture depth of 0.104 mm, as measured by the grease technique described earlier. This value is about half the texture depth of the float finished concrete surface also described earlier (see fig. 11).

Figure 35 presents values of locked wheel friction coefficient and hydrodynamic pressure plotted against runway distance for one run. These values were obtained at a carriage speed of 90 knots, almost twice the hydroplaning speed of 47 knots, with the ribbed-tread tire and a runway water depth of 0.3 inch. The runway surface condition is noted in figure 35; there were three sections, a smooth concrete section, the sandblasted textured concrete portion, and another smooth concrete section. With the air jet off, it can be seen that hydrodynamic pressures above 40 pounds per square inch were developed on the tire footprint and that very low values of μ_{skid} were obtained. But with the air jet on, there is a reduction in hydrodynamic pressure to near zero on the tire surface. Note also the great improvement of values of μ_{skid}, especially on the textured concrete section where the friction coefficient is greater than 0.4. The gradual decrease in μ_{skid} shown as the tire traveled over the sandblasted runway section is due to a nonuniform texture achieved during sandblasting as indicated in figure 34.

Figure 36 presents wet runway cornering force data as a percent of dry runway values plotted against the same runway distance as in figure 35. The yaw angle was 5°, the water depth was 0.3 inch, and the speed was 77 knots, which was once again greater than the critical hydroplaning speed. Note that with the air jet off, less than 5 percent of the dry runway cornering force is achieved; but, with the air jet on, more than 50 percent of the smooth tire dry runway cornering force is obtained in the textured concrete section.

Figure 37 summarizes results, such as those illustrated in figure 35, obtained with the locked wheel, the 4-groove ribbed-tread tire, and 0.3 inch of runway surface water. Here, the values of μ_{skid} of both smooth and textured runway surfaces are plotted against forward speed in knots. It can be seen that on the smooth concrete surface there is a relatively small difference between the curves obtained with the air jet off and the air jet on, because of the inability of the air jet to remove the very thin fluid film which adheres to the smooth surface. On the textured surface, however, the many surface irregularities puncture this thin surface film, and the result on friction coefficient is shown by the curves obtained on the sandblasted concrete. On this textured runway surface, which is perhaps smoother than actual runway surfaces in use today, much greater values of μ_{skid} are obtained with the air jet on than with the air jet off.

It is believed that the use of air jets will prevent tire operation in the reverted rubber mode during wet operations. The large gain in friction coefficients obtained through air jets means greatly increased wheel spin-up moments upon brake release or at touchdown. Therefore the prolonged wheel skids necessary to develop tread reversion should not occur during normal touchdown and braking operations.

Pavement Grooving

Pavement grooving is believed to offer great promise as a means of alleviating all forms of tire traction loss on wet runways. The following discussion attempts to describe some beneficial aspects as well as some possibly deleterious aspects of pavement grooving on aircraft and runway behavior.

Transverse grooves.- The idea of grooving runways transversely is not new. Several military airfield asphalt runways in England had transverse grooves installed at least 9 years ago. The work of Gray (ref. 20 and fig. 9) demonstrated that transverse grooves can greatly increase the critical water depth on the runway required for dynamic hydroplaning to occur, and thus reduce (by the higher rainfall precipitation rates required) the probability of aircraft to suffer dynamic hydroplaning. The increased traction due to transverse grooving of a flooded runway is illustrated by the wheel spin-up time histories measured at Langley and presented in figure 38. In this figure, wheel spin-ups from a locked wheel skid condition are presented on dry, and flooded, grooved and ungrooved, large aggregate asphalt surfaces under constant vertical load and inflation pressure conditions for a ground speed of 100 knots. The slope of the angular velocity-time curve during wheel spin-up is the angular acceleration, and thus indicates the amount of traction developed between the tire and ground. It can be seen that the transverse grooved section of pavement (picture shown in fig. 39) restored the traction developed by the tire on the flooded pavement to that obtained on the dry surface. This result indicates, for example, that installing transverse grooves in the touchdown areas of runways might prevent prolonged skids from developing on aircraft tires at touchdown and thus prevent the dangerous development of reverted rubber in the tire skid patch.

It has been previously shown in this paper that once reverted rubber is established in the tire footprint, extremely low friction coefficients develop on wet pavements down to very low ground speeds. Since, the friction coefficients that result are as low or even lower, in some cases, than the tire free-rolling resistance coefficient, μ_r, the tire has a tendency to remain in the locked wheel condition for long distances on the runway.

Recent tests at the landing loads track show that transverse pavement grooving can remove the reverted rubber in the tire footprint as the tire slides across the grooves and restore tire traction capability to normal rubber conditions. This dramatic result is shown in figure 39. This result (removing the reverted rubber) also reinforces belief in the concept that the reverted rubber acts as a seal around the edge of the footprint tending to prevent trapped fluid inside from escaping readily.

It can be seen from this discussion that transverse grooves on runways can effectively restore normal braking action to tires operating in the reverted rubber mode. It is felt that it is not necessary for the runway to be completely grooved to obtain this beneficial effect. For example, a short series of transverse grooves spaced every 200 feet or so along the runway may be sufficient to restore the tire to normal conditions if reverted rubber develops during a prolonged braking skid at any point during the landing roll. It should also be pointed out that there is merit in not grooving the entire width of a runway. Consider that only the middle third of a runway is transversely grooved. Let us assume that an aircraft touches down off runway centerline with one main landing gear operating on the grooved runway and the other gear outside the grooved area. When wheel braking commences, a higher braking force should be developed by the landing gear tire(s) operating on the grooves than the tire(s) off the grooves. This should produce a large stabilizing moment about the aircraft center-of-gravity, tending to return the aircraft to the center of the runway. This effect would be beneficial during crosswind landings on wet runways.

The deleterious effects of pavement transverse grooving on the runway itself, on aircraft vibrations, and on tire tread wear during dry or wet operations are as yet unknown. As a consequence, it is felt that it would be unwise at this stage of research to recommend unqualified use of transverse grooving on runways as a means of improving tire traction on wet pavements.

Certainly, the very promising results obtained thus far, indicate that full-scale research on actual runways needs to be performed to determine the nature of any bad side effects that might stem from transverse grooving. On the other hand, installing transverse grooves in paved runway overrun areas is to be recommended. Here, in times of emergency, the grooves would be available to help stop the aircraft yet the grooved surface would not interfere with normal operations. Also, some experience on pavement deterioration through weathering effects of the grooving could be established.

Some track tests were also conducted using longitudinal runway grooves and are described in the following section of the paper. However, as is indicated, the track results are not conclusive, and further full-scale aircraft tests on longitudinal pavement grooves need to be made.

Longitudinal grooving.- Several taxi runs were made at the track with the tire yawed (5°) over a flooded longitudinally-grooved pavement section at high ground speeds. It was found that the longitudinal grooves peeled the tread from the test tire. At first glance, this result would tend to preclude further tests on longitudinal grooves. Let us, however, look at this result in more detail. It is obvious that the grooves did develop large side forces on the tire tread. It is noted that the test carriage at the track is restrained from sideways motion by preloaded side wheels, and it is necessary then to question whether this detrimental tread effect would develop on a yawed but unrestrained vehicle such as an aircraft. For this case, the large side forces developed by the tires on the longitudinal grooves would tend to unyaw the aircraft by producing a very large stabilizing moment about the center-of-gravity. This means that the aircraft would tend to quickly align itself with the runway and reduce the side forces on the tires to zero values.

It is concluded then that the track result may not be valid for aircraft or other unrestrained vehicles such as automobiles. Obviously, full-scale tests using unrestrained vehicles are needed to determine longitudinal groove effects. The beneficial effect longitudinal grooving would have on aircraft during crosswind landings on flooded runways speaks for itself.

CONCLUDING REMARKS

It has been the purpose of this paper to illustrate the fundamental principles involved in tire traction losses that develop during aircraft operation on wet or flooded runways in the light of past and more recent research results. This paper shows that the hazards to aircraft ground operation resulting not only from dynamic and viscous hydroplaning but also from rubber tread reversion are real and can happen more frequently than was previously thought possible.

Future operations may not be as successful as in the past. The number of high performance jet aircraft in operation is increasing at a rapid rate. Also many more airports with shorter runways are expected to accomodate jet aircraft. The wet traction capabilities of existing aircraft braking systems and runway surfaces need to be improved; it is recommended that pavement and aircraft slipperiness research be expanded, especially in the areas of promise described in this paper, associated with pavement surface texture, pavement grooving, and air jet research and development.

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FRICTION COEFFICIENT VARIATION WITH SLIP RATIO

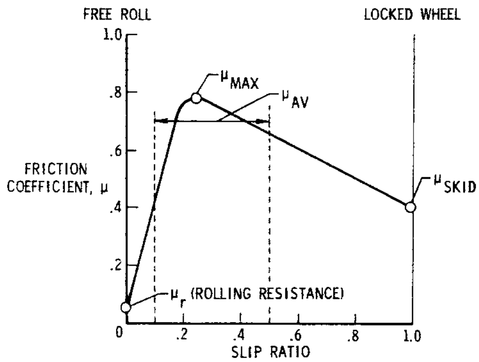


Figure 1

EFFECT OF SPEED ON FULL SKID FRICTION COEFFICIENT
DRY RUNWAY

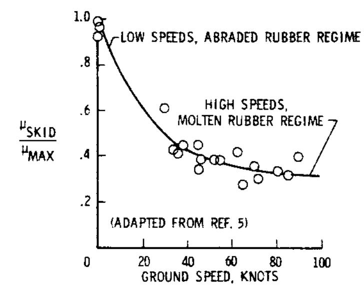


Figure 2

32 × 8.8 AIRCRAFT TIRE BLOWOUT
AFTER SKIDDING 60 FT ON DRY CONCRETE AT 100 KNOTS GROUND SPEED

Figure 3

STATIC FRICTION COEFFICIENT VARIATION WITH INFLATION PRESSURE
DRY CONCRETE; GROUND SPEED = 0.008-1.7 KNOTS

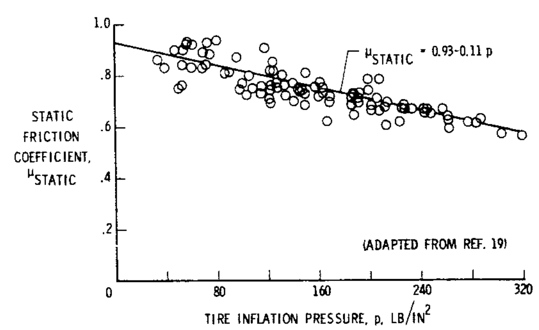
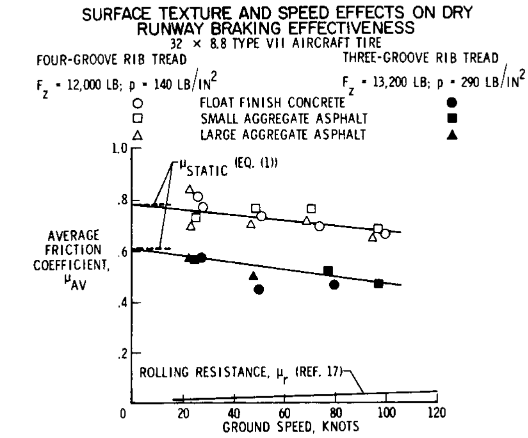


Figure 4



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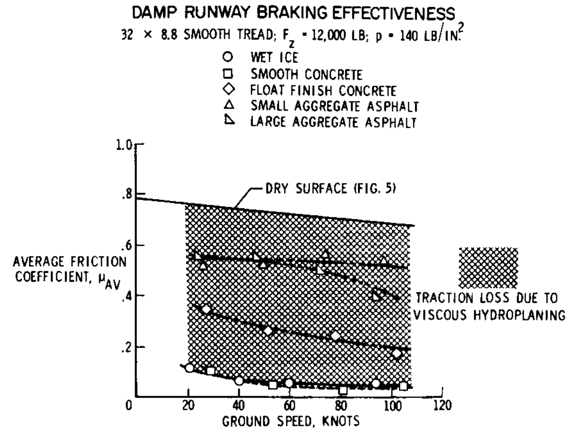

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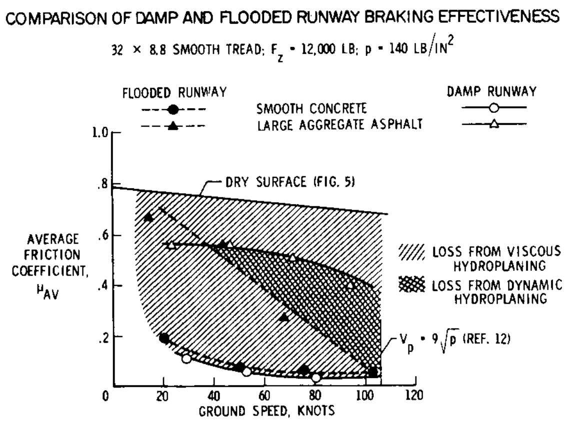
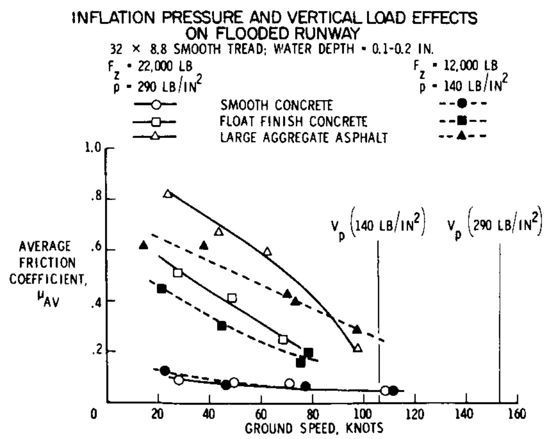


Figure 7



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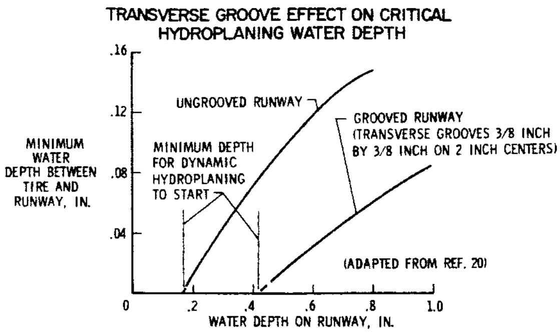


Figure 9

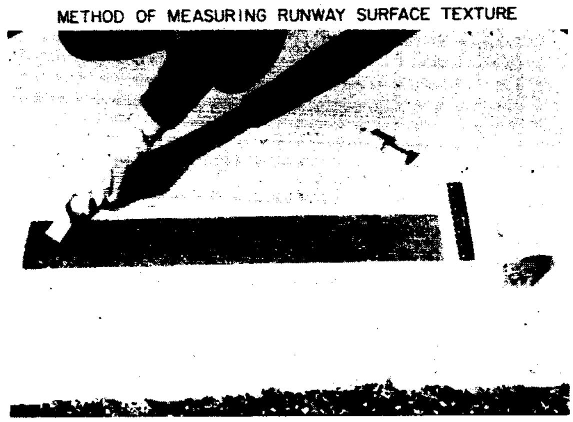
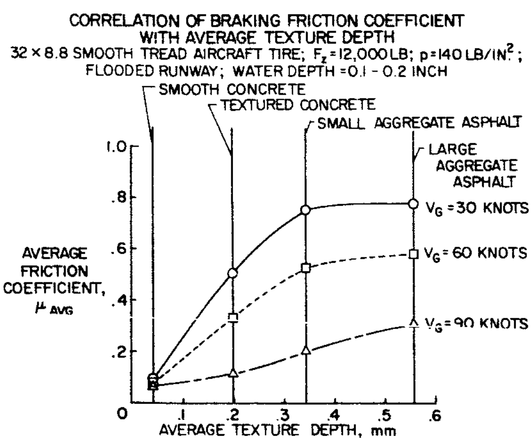


Figure 10



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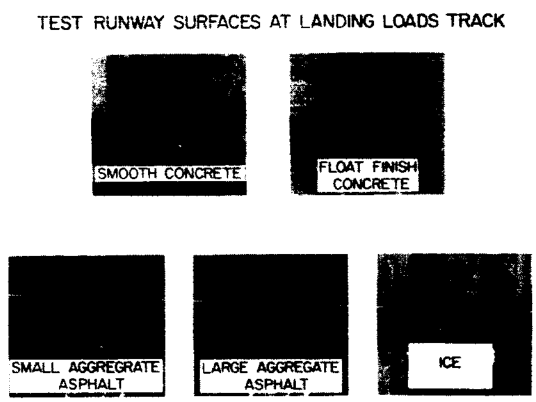

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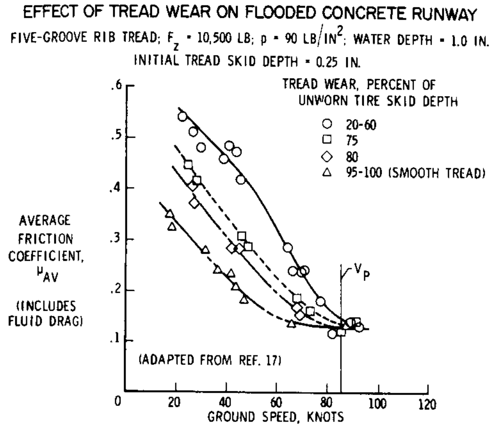

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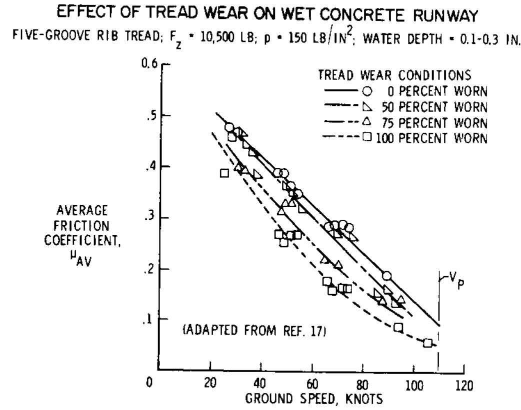

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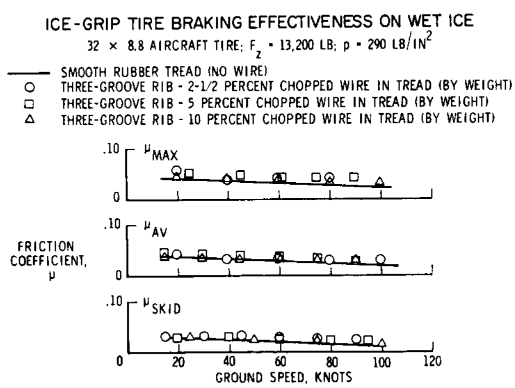


Figure 15

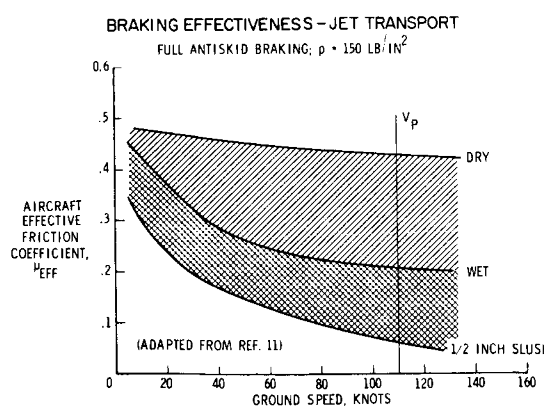
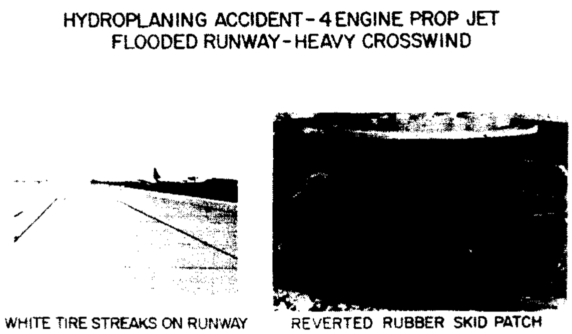


Figure 16



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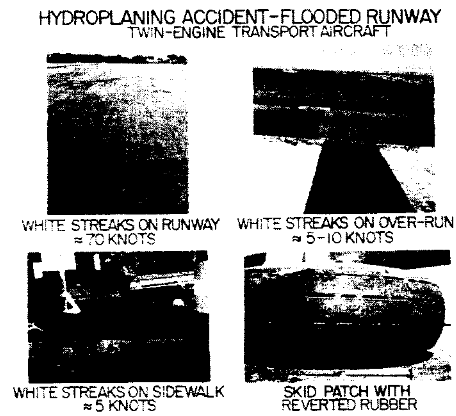

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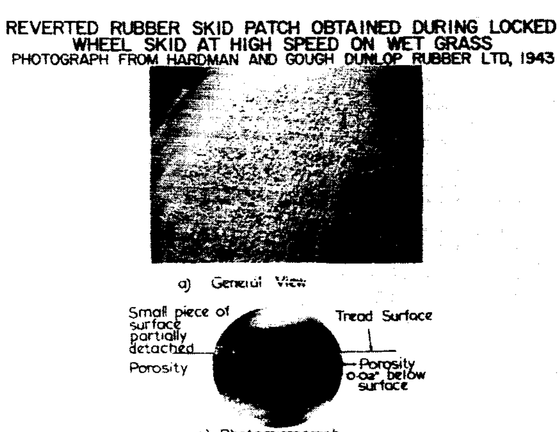


Figure 19

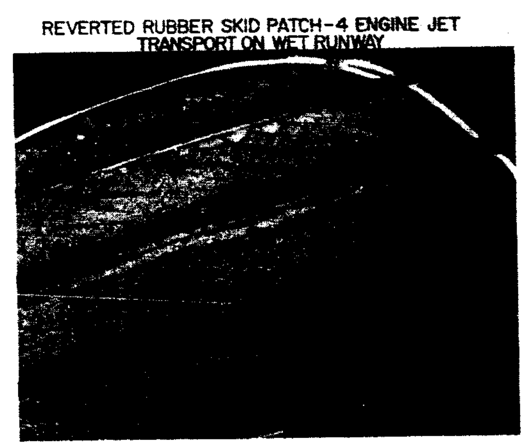


Figure 20

HYDROPLANING ACCIDENT-REVERTED RUBBER SKID PATCHES
RUNWAY WET-ISOLATED PUDDLES
SUPERSONIC FIGHTER TYPE AIRCRAFT

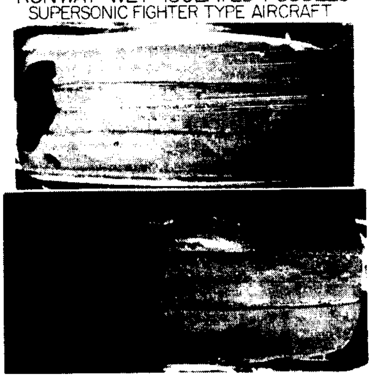


Figure 21

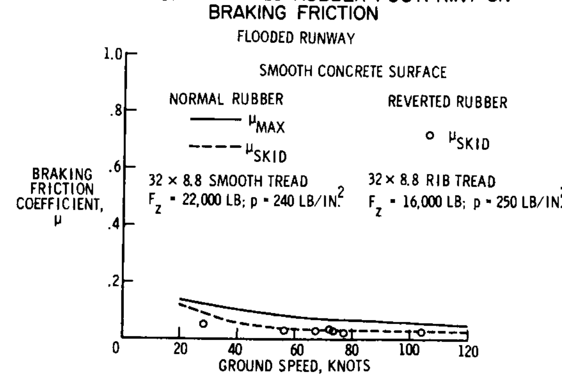
REVERTED RUBBER SKID PATCH-4 ENGINE PROP JET WET RUNWAY

Figure 22

REVERTED RUBBER SKID PATCH-LANDING LOADS TRACK
32×8.8 SMOOTH TREAD AIRCRAFT TIRE; F_z=16,000 LB; p=250LB/IN^2

Figure 23

EFFECT OF REVERTED RUBBER FOOTPRINT ON BRAKING FRICTION



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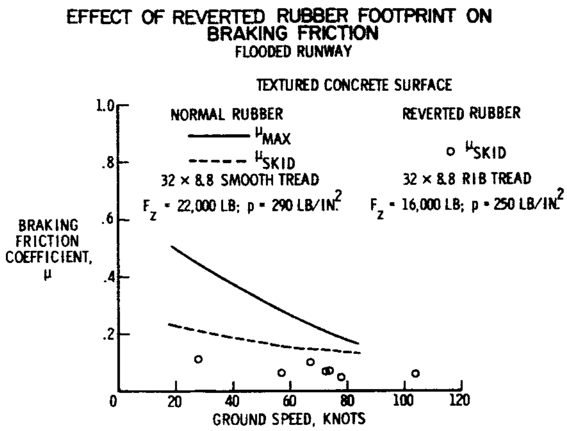


Figure 25

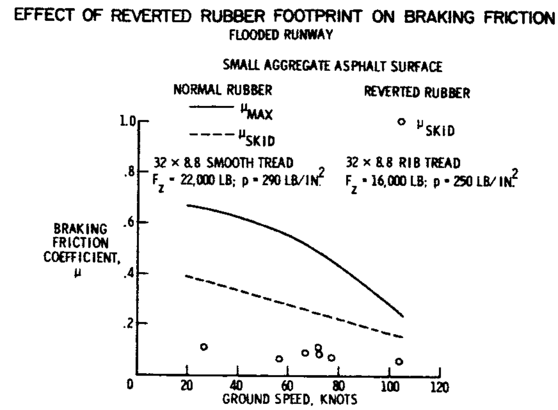


Figure 26

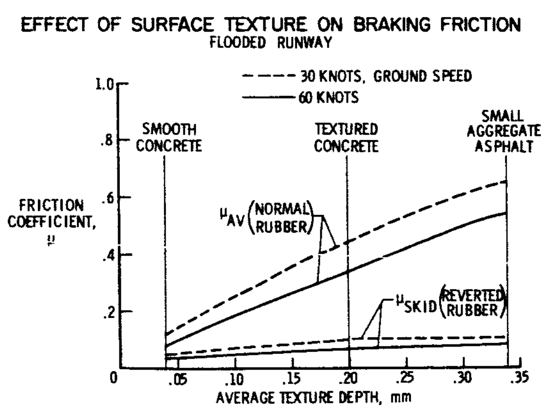


Figure 27

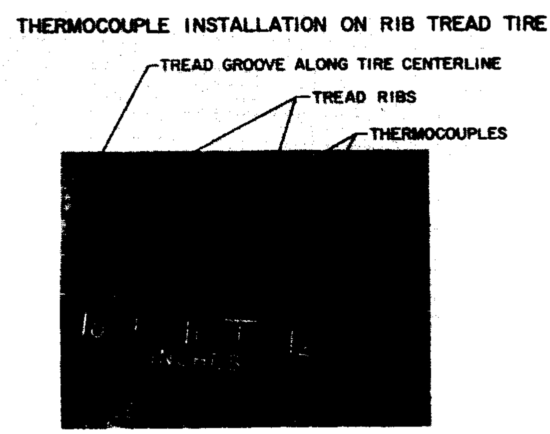


Figure 28

TREAD SURFACE TEMPERATURE RISE DURING PROLONGED SKID
AFTER 65-FOOT SKID ON DAMP SMOOTH CONCRETE; AMBIENT TEMPERATURE = 82° F

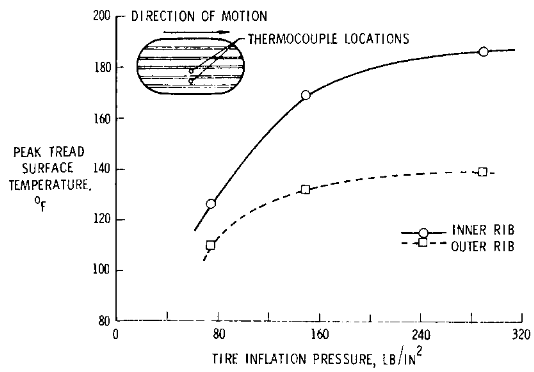


Figure 29

TREAD SURFACE TEMPERATURE AND FULL SKID FRICTION COEFFICIENT TIME HISTORIES
LOCKED WHEEL SKID AT 77 KNOTS GROUND SPEED; F_z = 10,000 LB; p = 150 LB/IN²

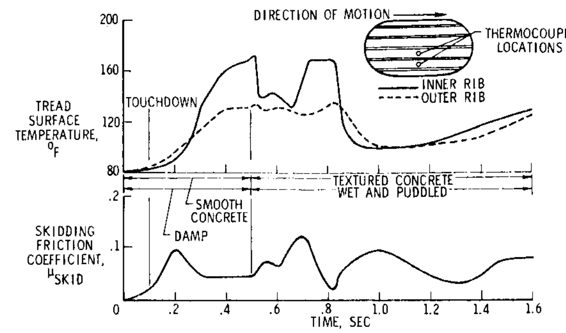


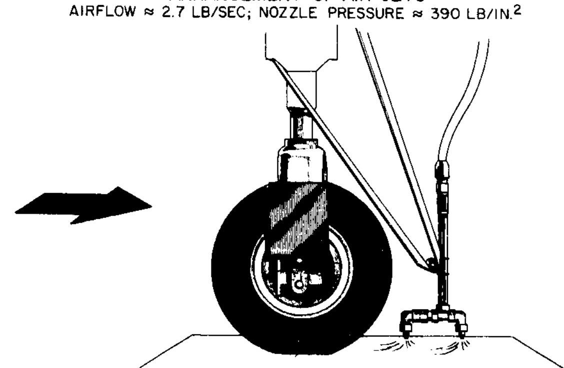
Figure 30

HYDROPLANING ACCIDENT - 4 ENGINE-PISTON TRANSPORT
LARGE AREAS OF RUNWAY COVERED WITH WATER DURING LANDING

NOTE: DEPOSITED RUBBER IN SKID MARKS OCCUR DURING CHANGE IN RUNWAY SURFACE TEXTURE

Figure 31

ARRANGEMENT OF AIR JETS
AIRFLOW ≈ 2.7 LB/SEC; NOZZLE PRESSURE ≈ 390 LB/IN.²



ADAPTED FROM REF. 18

Figure 32

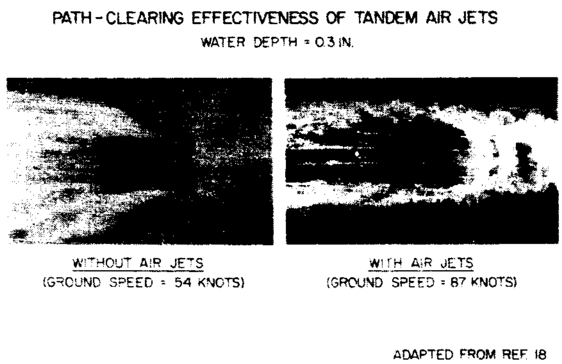


Figure 33

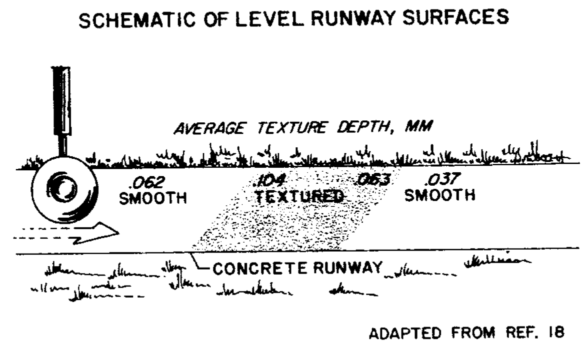


Figure 34

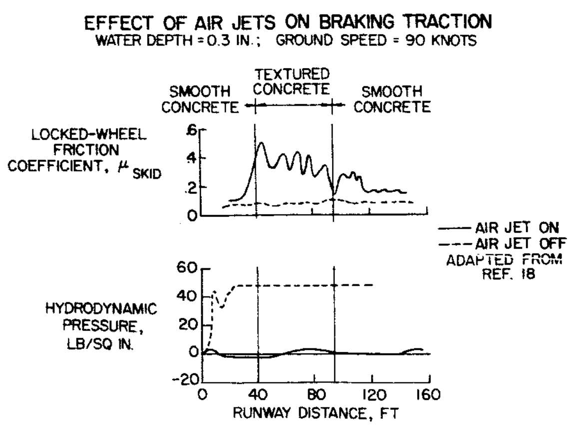


Figure 35

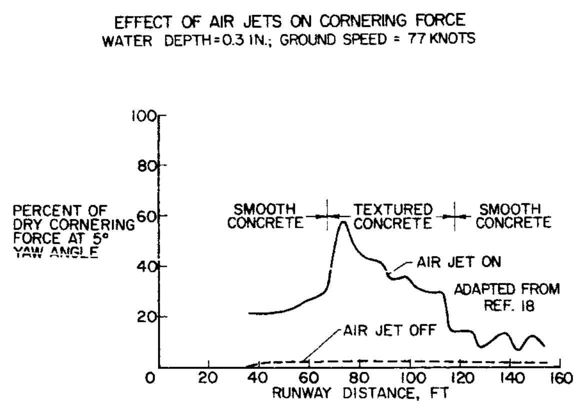


Figure 36

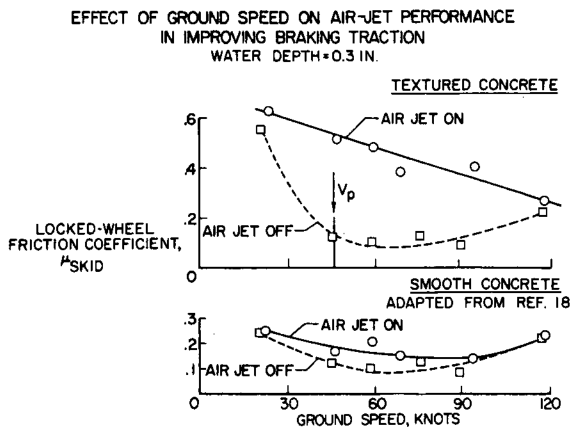


Figure 37

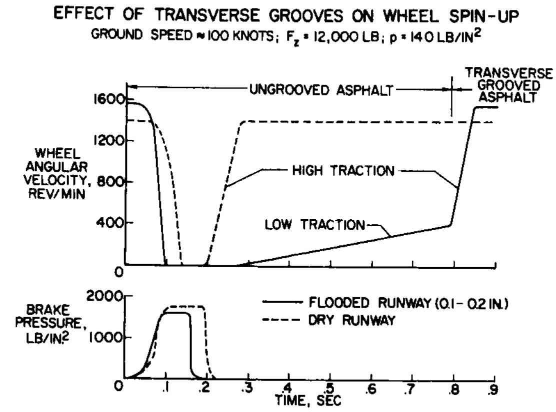


Figure 38

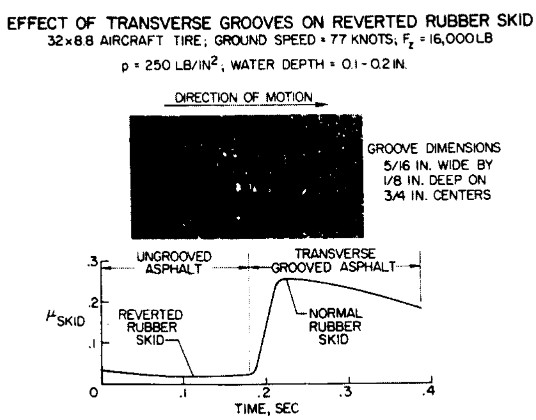


Figure 39

NASA-Langley, 1965